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A Source for Field-Aligned Currents at Auroral Latitudes

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Energetic plasma drifting toward the earth from the plasma sheet in the earth's magnetospheric tail is terminated by an inner boundary (the Alfvén layer). Sheets of field-aligned current (Birkeland currents) flow down to the ionosphere from this plasma boundary. The mechanism for generating the current is essentially that originally proposed by Alfvén in 1939. A certain amount of charge separation develops in the Alfvén layer because the geocentric drift paths of ions and electrons are not coincident within the layer. The charge separation produces an electric field that is perpendicular to B and is transmitted along lines of force to the ionosphere. Currents flow across magnetic field lines in the ionosphere and along the magnetic field lines to the Alfvén layer. The electric field is reduced by these currents, which flow to neutralize the charge separation. The position of the Alfvén layer is such as to produce a current sheet that enters the ionosphere at auroral latitudes. The Birkeland current necessary to neutralize the Alfvén layer is calculated to be about 10^6 amps, which is sufficient to produce the transverse magnetic disturbances of about 100 γ that have been observed by satellites in auroral latitudes; the thickness of the Alfvén layer corresponds to the width of the zone of these transverse magnetic disturbances. Finally, the Birkeland current is related to a larger current system that includes the *DS* current system.

Introduction

Ionospheric currents that couple to currents flowing parallel to the local magnetic field were first proposed by *Birkeland* [1908, p. 95 ff.] to explain the polar elementary substorm (magnetic-bay disturbance) and other polar magnetic disturbances. Hence, we will call such field-aligned currents Birkeland currents.

Boström [1967] and *Cummings and Dessler* [1967] have interpreted the satellite data of *Zmuda et al.* [1966, 1967] as showing that there is a flow of field-aligned current into the auroral zone. The data indicate that the currents flow almost continuously and take the form of funnel-shaped sheets coming into both northern and southern auroral zones. This interpretation has been discussed by *Boström* [1964], who has recently presented an excellent review of the physics of field-aligned currents [*Boström*, 1968].

While mechanisms have been proposed that produce field-aligned currents in localized regions [e.g., *Fejer*, 1961; *Swift*, 1965; *Cummings*, 1966], only the mechanism proposed by *Alfvén* [1939, 1940, 1950], *Martyn* [1951], and *Kern* [1962] produce a funnel-shaped-current distribution that is connected to the auroral zones. Martyn's mechanism for the field-aligned current is based on a faulty model for the main-phase ring current in which the particles circle the earth without executing cycloidal (trapped particle) motion. Kern's mechanism requires trapped radiation to be entirely confined to auroral-zone field lines. The mechanism proposed by Alfvén, however, is fundamentally sound although, as we shall see in the Discussion section, the current system he proposed is not complete. Alfvén's mechanism produces a current system driven by an electric field induced by a charge separation that arises because of the different drift paths of ions and electrons moving in a combined electric field and nonuniform magnetic field.

Rocket and satellite measurements of the past few years have developed a physical model that is different from the one used by Alfvén. In this paper we point out, in a qualitative way, how the present-day model of the magnetosphere together with Alfvén's basic ideas can account for the average properties of the observed funnel-shaped distribution of Birkeland currents. The fine structure and detailed time-dependent behavior of the current distribution are not explained.

The Model

The mechanism presented here for the generation of Birkeland currents requires organized flow of plasma within the magnetosphere. The general pattern of large-scale magnetospheric circulation originally proposed by *Axford and Hines* [1961] has received substantial experimental and theoretical support (e.g., see *Brice* [1967]; *Freeman* [1968]; *Freeman et al.* [1968]; *Dessler* [1968*a*]; the review paper by *Obayashi and Nishida* [1968]; and the references cited in these papers). The circulation is, in our view, driven by merging of magnetic field lines in the geomagnetic tail. (The energy source for the entire process is, of course, the solar wind, which puts magnetic energy into the system by causing a geomagnetic tail to be formed. Part of the magnetic energy destroyed by merging of field lines in the tail appears in the large-scale magnetospheric circulation pattern.)

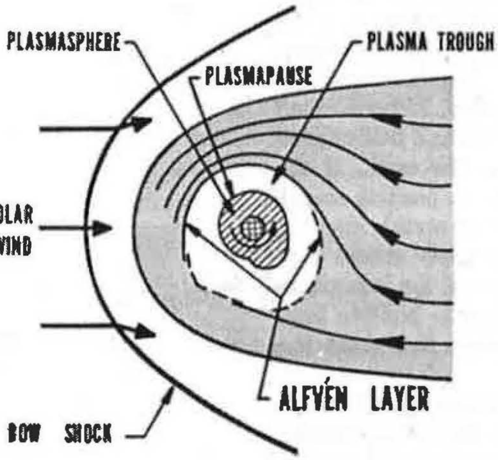

Fig. 1. Sketch of plasma flow in the equatorial plane as seen from above the North Pole during a magnetically disturbed period. The plasma flows from the tail through the magnetosphere, the flow pattern being skewed by the electric field produced by the corotation of the plasmasphere with the earth. This flow pattern is essentially that given by *Brice* [1967]. The principal modification is that the inflowing plasma is turned away from the earth before it reaches the plasmapause [*Freeman and Maguire*, 1967]. The width, sharpness, and location of the Alfvén layer is a complex function of ionospheric conductivity, energy spectra, plasma sheet particles, and magnetospheric electric fields, all of which vary with local time. The question of whether the plasma flows out through the front of the magnetosphere [*Dungey*, 1961] or back along the flanks inside the magnetosphere [*Axford and Hines*, 1961] is left unresolved. The Alfvén layer is formed along the inner edge of the plasma flow.

One of the consequences of such a circulation system is an electric field impressed across the magnetosphere. In the equatorial plane, this electric field is directed approximately at right angles to the earth-sun line from the dawn to dusk side of the magnetosphere, although not necessarily extending all the way to the magnetopause. The experimental data show that the energetic plasma in the geomagnetic tail is in the form of a sheet confined to the vicinity of the magnetic neutral sheet [*Bame et al.*, 1966, 1967; *Bame*, 1968; *Vasyliunas*, 1968*a*]. The general circulation pattern causes plasma from the plasma sheet to flow toward the earth from the tail. As the plasma gains energy with the increasing magnetic field strength, gradient drift forces should become important so that the drift paths of the electrons and protons will separate. Above and below the equatorial plane, the plasma sheet splits into two cusps that encircle the inner magnetosphere [*Vasyliunas*, 1968*a*]. The plasma flow around the earth shown in Figure 1 and the configuration in the noon-midnight meridian shown in Figure 2 follow from the above considerations. *Freeman and Maguire* [1967] and *Vasyliunas* [1968*a*] have shown that the Alvén layer moves toward the earth during magnetically disturbed times.

The problem of a plasma drifting in crossed E and B fields in the vicinity of a point dipole was treated almost three decades ago by *Alfvén* [1939, 1940]. The results of his calculations of drift paths for electrons are shown in Figure 3. Similar calculations have been carried out recently by *Kavanagh et al.* [1968] for the case of a more realistic magnetosphere with a corotation electric field. Their calculations give a flow pattern in agreement with Figure 1, and the basic findings of Alfvén concerning proton and electron orbits remain valid.

Ions and electrons of equal energy drift along paths that, to first order, are mirror images as reflected along the Y axis in Figure 3. These differing drift paths lead to a charge-separation layer along the dipole side of the drift paths. We have illustrated this effect in Figure 4 for the case of unequal electron and ion energies. The asymmetrical, noncircular drift paths for

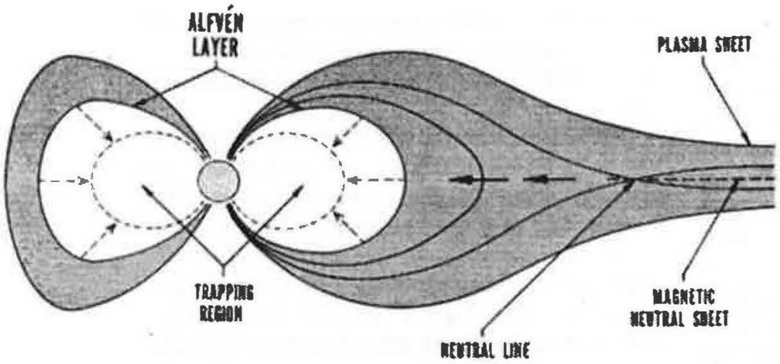

Fig. 2. The plasma sheet configuration in the noon-midnight meridian (after *Vasyliunas* [1968*a*]). The Alfvén layer, at the inner surface of the plasma tends to form a complete, closed shell around the inner magnetosphere. As the plasma moves closer to the earth during increasing magnetic activity, the Alfvén layer moves inward as shown by the dotted lines. The Van Allen radiation is found inside the trapping region.

ions and electrons lead, in general, to a charge-separation layer along the earthward boundary of the drift paths. It is specifically this charge-separation layer that forms the Alfvén layer. The magnitude of the charge-separation in the Alfvén layer is, of course, limited by other charges within the magnetosphere that move so as to maintain approximate charge neutrality.

GENERATION OF BIRKELAND CURRENTS

The following is an adaptation of the mechanism originally proposed by Alfvén in 1939 as illustrated by Figure 5 from his original paper. For our present purposes, details of the drift paths of the plasma particles coming into the magnetosphere from the plasma sheet need not be considered; the calculations represented by Figures 3 and 4, or the more detailed work of *Kavanagh et al.* [1968], argue strongly that an Alfvén layer must develop along the inner edge of the drifting plasma as a normal consequence of the different drift paths for ions and electrons.

The charge separation at the Alfvén layer can be of either sign with either the ions or the electrons drifting closer to the dipole. This effect is illustrated in Figure 6 for the case where the electrons have drifted closer to the earth forming a sheath of negative charge. This charge can be neutralized in one of two ways: (1) The electrons can repel each other and discharge into the ionosphere, or (2) ions can be brought up from the ionosphere. The second method is physically the most likely; the electrons are energetic ($\sim 10^3$ ev), and their mirroring action will resist their being pushed down into the ionosphere. The thermal ions in the ionosphere, on the other hand, are moved upward relatively easily to yield charge neutrality. Either method of charge neutralization produces a field-aligned current directed away from the earth. If the Alfvén layer were to develop a positive charge (with ions drifting closer to the earth), many of the same arguments would apply except that electrons would be raised out of the ionosphere to neutralize the more energetic positive ions. The current in this case would flow down the field lines toward the earth.

The current path should be completed through the ionosphere, both out into the neutral plasma adjacent to the charge sheath and into the *DS* current system. As indicated in Figure 6, the current is probably once again largely carried by ionospheric particles since they are easier to move than the more energetic particles that have drifted in from the plasma sheet.

The neutralizing currents must flow even in steady-state conditions. The thermal electrons (or ions) that rise to neutralize the charge sheath will be swept out of the sheath by the transverse electric field that brings in the more energetic plasma-sheet particles. Since the thermal particles experience only electric field drift and negligible gradient drift, they will move on different drift paths and at different speeds from the energetic particles. The distribution of current within the Alfvén layer will depend in a complex way on the energy spectra of the ions

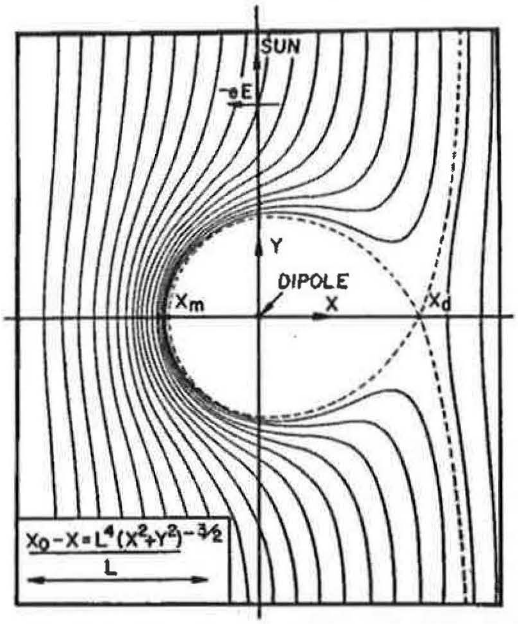

Fig. 3. Drift paths of electrons in the equatorial plane of a magnetic dipole with a superimposed uniform field and a perpendicular electric field [*Alfvén*, 1939; *Alfvén and Fälthammar* (Fig. 2.10, p. 56), 1963]. L is the scale of the flow pattern and is proportional to the fourth root of the particle energy. The drift path for ions of the same energy would be the mirror image reflected along the Y axis. Rotation of the dipole and the attendant problems of corotation were not considered. The asymmetrical drift paths for ions and electrons leads to a charge-separation layer near the dipole where particles of opposite sign are separated by the drift motion. This charge separation layer is called the Alfvén layer. Alfvén proposed that field-aligned currents would flow from this layer into the ionosphere (see Figure 5). Although certain details in this figure must be changed to be consistent with the magnetospheric model used here (e.g., the electric field vector should be reversed and other field-aligned currents are present) the basic physical process leading to a charge-separation layer remains as proposed by Alfvén.

and electrons from the plasma sheet and from the ionosphere. Furthermore, time variations in the electric field or the particle spectra will create complex structure within the Alfvén layer. The resulting Birkeland currents will show corresponding structure in both space and time. For example, when the Alfvén layer moves inward into the plasma trough, transient electric fields aligned parallel to the magnetic field should be created. At such times, especially intense Birkeland currents would be generated.

We will first evaluate the thickness of the layer and show that it is consistent with the width of the auroral region of transverse magnetic disturbances as observed by *Zmuda et al.* [1966, 1967]. The current necessary to neutralize the unbalanced charge is then evaluated and is found to be sufficient to produce the observed amplitude of the transverse magnetic disturbances.

The thickness of the Alfvén layer. The Alfvén layer is taken to be the region where the convection of plasma tends to produce an un-

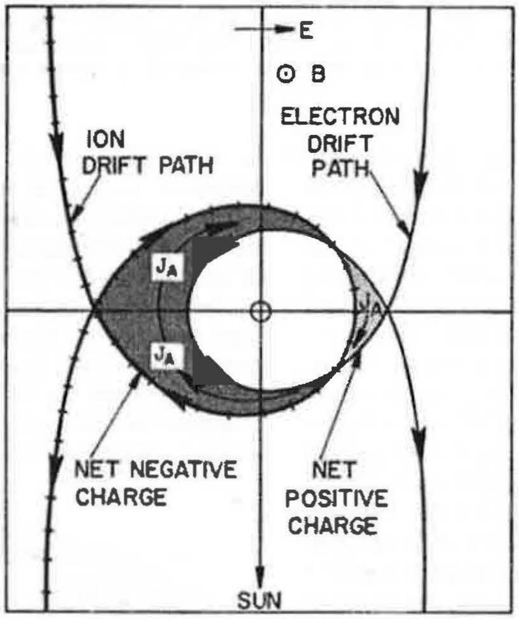

Fig. 4. Innermost drift paths of protons and electrons moving in a dipole magnetic field with a superimposed uniform field and a perpendicular electric field shown for the case where the protons have three times the energy of the ions. J_A is a partial ring current set up within the Alfvén layer by gradient drift motion. This configuration illustrates the results of the flow of plasma sunward from the geomagnetic tail. In this illustration, most of the inner edge of the Alfvén layer has a net negative charge; a net positive charge should accumulate on the dusk side of the earth. This configuration ignores charge-separation and corotation electric fields. The deviation from charge neutrality in the shaded areas is very slight because other charges within the magnetosphere move so as to maintain charge neutrality. The neutralization cannot be complete, even in steady-state conditions. The flow of neutralizing charge produces the field-aligned currents.

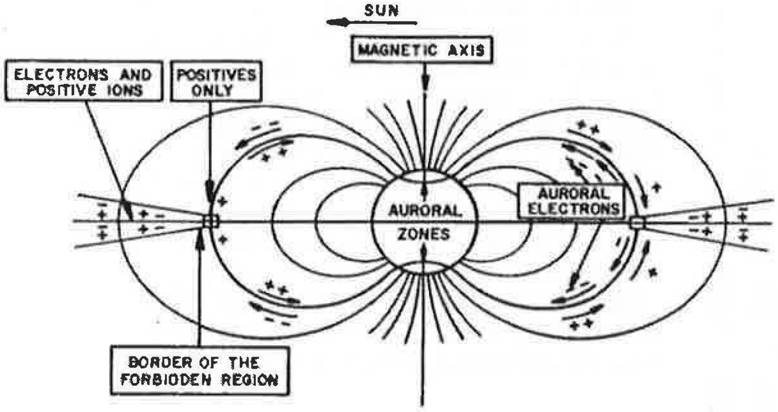

Fig. 5. 'The discharge along the magnetic lines of force between the equatorial plane and the auroral zones' [*Alfvén* (Fig. 5, p. 16), 1939]. The reader should note that the over-all current system, as shown in Figure 8, cannot be obtained by simple neutralization of the Alfvén layer.

balanced charge. Its thickness depends principally on the conductivity of the ionosphere and the spread of energies of the particles that form the plasma sheet. The thickness of the Alfvén layer is easily calculated for two limiting cases: (1) a highly conducting ionosphere and (2) an insulating ionosphere. We will assume, for simplicity, that the electron and ion energy spectra are very narrow (i.e., nearly monoenergetic). The boundary condition of a highly conducting ionosphere allows sufficient current to flow so that charge neutralization of the Alfvén layer is essentially complete. For this case, the electric field associated with the particle drift motion is not significantly modified by the Alfvén layer. Figure 4 may be taken as an illustration of the results of a typical calculation for the case where charge neutralization of the Alfvén layer by the ionosphere is complete; the maximum thickness for this arbitrary choice of particle energies is about 5 R_E. For the second case of an insulating ionosphere, intense charge separation fields (of about 10 v/m) prevent the thickness from growing much beyond a cyclotron radius or a Debye length [*Karlson*, 1963; *Helmer*, 1963; and *Block*, 1966]. That is, the electric field arising from charge separation in the Alfvén layer quickly builds up to the point that the particle drift paths are modified, and further charge separation is severely inhibited.

The true situation is, of course, intermediate between these two extremes. While we do not solve here the complete, self-consistent form of the drift paths, we can show that the electric field from charge separation does not completely dominate the electric-field pattern in the Alfvén layer. The electric field perpendicular to the magnetic field in the auroral-zone ionosphere has been shown to be ~10 mv/m [e.g., see *Föppl et al.*, 1968]. This electric field, when conducted along field lines into the equatorial plane, is reduced to 0.3 mv/m. (The decrease in electric field strength is such as to keep the potential difference between field lines constant.)

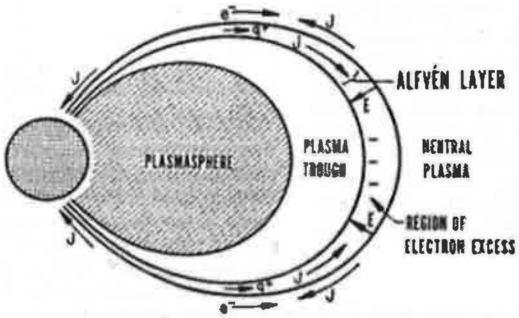

Fig. 6. An electron sheath developed at the inner edge of the Alfvén layer. The charge separation arises because of the different drift paths for ions and electrons in the Alfvén layer. In steady-state conditions a current J must flow down the magnetic field lines to the ionosphere. Particles for the neutralizing current should come out of the ionosphere (indicated as q^+ ions and e^- electrons). The current loop can close either into the neutral plasma as shown or into the *DS* current system as schematically shown in Figure 8.

This electric field strength is approximately equal to that associated with the magnetospheric convection [cf., *Brice*, 1967; *Vasyliunas*, 1968*b*]. Observation of stronger electric fields (~100 mv/m) during auroral events is likely to be associated with stronger convection electric fields. Therefore, the electric field in the Alfvén layer due to charge separation modifies the pure convection electric field but does not completely dominate it. The particle orbits will be perturbed from those shown in Figure 4, but not to the extent shown in the calculations of *Karlson* [1963], *Helmer* [1963], and *Block* [1966]. The thickness of the Alfvén layer should be only somewhat less than illustrated in Figure 4.

In summary, the thickness of the Alfvén layer is theoretically determined for monoenergetic electrons and ions to be between 10^3 meters for zero ionospheric conductivity and several earth radii for high ionospheric conductivity. For realistic ionospheric conductivities and breadth of particle spectra, an Alfvén layer about 2 R_E thick at its thickest point would seem a reasonable estimate.

The width of the Alfvén layer should map onto the width of the region of transverse magnetic disturbances discussed previously. The average width of the latter region is 3° to 4° latitude during magnetically quiet times and increases to between 4° and 6° for $Kp \geq 4$ [*Zmuda et al.*, 1966]. However, latitudinal widths as small as 24 km or ¼° latitude have been observed (A. J. Zmuda, personal communication). In a dipole field the latitudinal width $d\Lambda$ between two magnetic shells is related to their equatorial width dL by $dL = 2L \tan\Lambda d\Lambda$. For $L = 6$, this reduces to $dL = d\Lambda/2$; while for $L = 10$, $dL = d\Lambda$, where L is in earth radii and $d\Lambda$ is in degrees. On this basis, the 2 R_E width of the Alfvén layer corresponds to auroral zone widths of 2° to 4°, values that are in general agreement with the width of the region of transverse magnetic disturbances.

A more precise evaluation can be made using the geomagnetic field configuration illustrated in Figure 7 [*Schield*, 1968]. The 2° separation between the 66° and 68° or 68° and 70° field lines maps onto an equatorial separation of 2 R_E in the midnight meridian. In the noon meridian, the 4° separation between the 72° and 76° field lines maps onto an equatorial separation of 1 R_E. Thus, the correspondence of these widths is in fairly good agreement with the expected width of the Alfvén layer.

The magnitude of the Birkeland current. We can easily estimate the steady-state current from the rate at which plasma flows in from the tail.

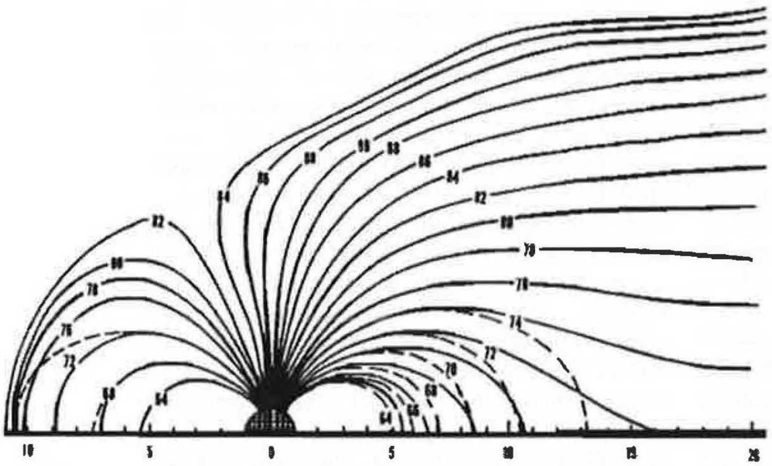

Fig. 7. A model of the configuration of the geomagnetic field in the noon-midnight meridian plane [*Shield*, 1968]. This configuration includes the quiet-day ring current field and a realistic tail field of 15 γ. This model predicts that the auroral-zone field lines do not map onto either the neutral sheet or the surface of the magnetosphere but are buried deep within the magnetosphere. However, the inner edge of the plasma sheet, located at 10 to 12 R_E [*Vasyliunas*, 1968*a*], does appear to be coincident with magnetic field lines that map onto the auroral zones.

If we assume an electric potential difference across the tail of ~50 kev [*Brice*, 1967], an inward flow speed of 12 km/sec results at about 20 R_E. At this distance, the plasma sheet is about 8 R_E thick, 40 R_E wide, and contains of the order of 1 electron/cm^3 [*Bame et al.*, 1967; *Vasyliunas*, 1968*a*]. This leads to a total inward electron (and ion) flux of 10^{26} electrons (and ions)/sec entering the magnetosphere. If we provisionally assume that 10% of these particles end up in the Alfvén layer, a total Birkeland current of about 2×10^6 amperes flows into the auroral zone.

The magnitude of the Birkeland current may be estimated more quantitatively as follows: The Birkeland current is determined by the rate at which the low-energy neutralizing plasma is swept out of the Alfvén layer. At the thickest part of the Alfvén layer (the dusk meridian in Figure 4), the electric-field drift of the neutralizing plasma is perpendicular to a magnetic lune with an area of the order of $(LdL)R_E^2$ where L is the equatorial crossing distance of the lune. (A magnetic lune is a surface perpendicular to a magnetic shell and bounded by two magnetic field lines.) Gradient drifts are not important for the neutralizing plasma because of its low energy. The product of the area of the lune, the charge density of the neutralizing plasma (equal to the charge density of the energetic plasma-sheet particles in the Alfvén layer), and the electric-field drift speed gives roughly the total current of neutralizing plasma being lost from the Alfvén layer. The drift speed is of the order of E/B where E is the magnitude of the convection electric field. The total current J_s necessary to supply the neutralization charge in the Alfvén layer is, therefore, $J_s = neEL^4R_E^2dL/B_0$, where B_0 is the geomagnetic field strength at the earth's equator. For $B_0 = 3 \times 10^{-5}$ w/m, $E = 0.3$ mv/m, and $dL = 2$, the total current is about 10^6 amps for $n = 1/\text{cm}^3$ and $L = 10$; the current is about 4×10^6 amps for $n = 10/\text{cm}^3$ and $L = 6$. Thus, both methods yield total currents in order of magnitude agreement with that deduced by *Cummings and Dessler* [1967] from satellite data.

The magnetic field produced by a current sheet for most simple geometries is of the order of $\Delta B \sim \mu_0 j_s$ where j_s is the auroral-zone Birkeland-current density. If we assume the Birkeland current is distributed uniformly around the auroral zone, the sheet current density is $j_s = J_s/2\pi R_E \cos\lambda$ amp/m where λ is the magnetic latitude, and $\Delta B \sim \mu_0 J_s/2\pi R_E \cos\lambda$. For $J_s = 10^6$ amperes and $\lambda = 70°$, we find that $\Delta B \sim 10^2\ \gamma$.

DISCUSSION

The merging of magnetic field lines across the neutral sheet in the geomagnetic tail causes a flow of plasma toward the earth, as first suggested by *Dungey* [1961]. This flow can be regarded as a sort of magnetospheric wind. The earth and its surrounding ionosphere and corotating plasmasphere represents a conducting obstacle to the plasma flow. The electric field induced by the plasma flow causes large-scale, field-aligned currents to flow into and out of the ionosphere and a *DS* current system to flow within the ionosphere. (These large-scale, field-aligned currents are generated by basically the same mechanism that causes a current to flow when the solar wind strikes a conducting object [cf., *Dessler*, 1968*b*].) These field-aligned currents (actually, body currents induced by the magnetospheric wind) flow into and out of large areas covering the centers of the *DS* current-system loops. The necessity for such field-aligned currents has been discussed by *Vasyliunas* [1968c].

The Alfvén mechanism for generating field-aligned currents may alternately be regarded as similar to that of partial ring currents, which generate field-aligned currents by the charge separation arising from gradient-drift motion [cf., *Cummings*, 1966]. In fact, one might consider the Alfvén layer as a partial ring current that acts to modulate and localize the large-scale field-aligned current produced by the magnetospheric wind. This process is illustrated in Figure 8. Note that the polarization electric field E_p tends to cancel the general magnetospheric electric field E, thus stabilizing the Alfvén layer on the night side so that a relatively thin, well-defined layer is maintained. On the day side, the net electric field tends to sweep the Alfvén layer away from the earth and out of the magnetosphere. Therefore the Alfvén layer on the day side should be thicker and less well-defined.

As shown in Figure 8, there should be a gap in the Birkeland current structure on the day side. The local time of this gap will be dis-

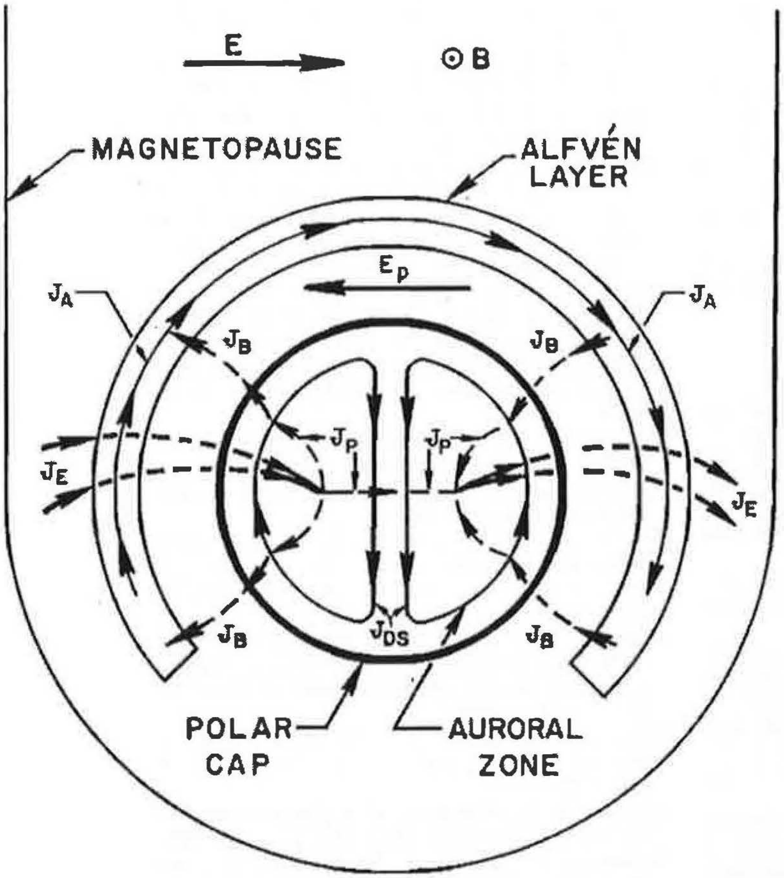

Fig. 8. Schematic sketch showing relationship between Birkeland currents, Alfvén layer, and *DS* current system. J_E is a broad, field-aligned current generated by the convection electric field *E*. This current flows into and out of the *DS* current system loops [see *Vasyliunas*, 1968*c*]. J_P is the Pederson current associated with the *DS* current system, J_B is the Birkeland current, and J_A is the ring current component of the Alfvén layer. E_p is the polarization electric field generated by the charge separation in the Alfvén layer. This field is not strong enough to completely cancel the convection field *E*.

placed from the indicated noon position (probably toward earlier hours) by asymmetries introduced by the *DS* current system.

The Birkeland current carries only part of the total current discharged into the polar caps by the convection electric field. However, the Birkeland current is more concentrated, and its higher current density is more easily detected. Also, the Birkeland current exhibits structure that indicates closely spaced and oppositely directed current flows. Figure 8 should be taken to be a schematic diagram showing net current flows. More complex, fine-scale structure is evidently superimposed.

In this paper we have pointed out how the Alfvén layer controls both the magnitude of the Birkeland current and its location. The magnitude and configuration of this current depends on many factors such as the energy spectra of particles in the Alfvén layer, the width of the layer, and distortions of the electric field pattern from the simple one assumed here. However, the estimates given in this paper show that both the current location and the current strength necessary to produce the transverse magnetic fluctuations observed by *Zmuda et al.* [1966, 1967] are consistent with the concept of an Alfvén layer. Additional study is required to make this description more complete and to learn what role the Alfvén layer and Birkeland currents play in other auroral-zone and polar-cap phenomena.

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